Characterization of Second Harmonic Afterburner Radiation at the

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Utilizing the Micro-Bunched Electron Beam

- At FEL saturation, the electron beam is highly micro-bunched at odd and even harmonics.
- Adding extra undulators (resonant at any of these harmonics but with different parameters) can be used to produce an additional FEL quality photon beam with properties such as
  - Enhanced harmonics content
  - Various types of planar and circular polarization (fundamental or 2nd harmonic)
  - ...


- Those extra undulators are generally referred to as “After-Burners”, AB.
- The After-Burner concept is being tested at the LCLS in the form of a Second Harmonic After-Burner (SHAB).

  Z. Huang and S. Reiche, *in Proceedings of the 2004 FEL Conference*, 201-204
Testing the After-Burner Concept

- In the LCLS, saturation occurs well before the end of the undulator even at the shortest wavelength.
- The last 10 of the 33 LCLS undulator segments have been set aside for the SHAB test.

![Diagram showing existing LCLS undulator with wavelength and harmonic information]
Testing the After-Burner Concept

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\[ 16 \text{ keV} = 0.75 \text{ Å (up to 20 keV} = 0.62 \text{ Å at 15 GeV) \]

\[ \text{existing LCLS undulator} \quad \text{2nd harmonic after-burner} \]

- Presently, the last 5 undulator segments (U29 – U33) have been converted to SHABs
Expected Second-Harmonic Afterburner Yield

Smaller $\beta$ function in afterburner will help

GENESIS simulation with $I_{pk}=3$ kA, $Q=250$ pC, $\varepsilon_n=0.6$ $\mu$m, $\Delta p/p=10^{-4}$ at $E=14$ GeV.
K Requirement

\[ K = \sqrt{K_0^2 / 2 - 1} \]

LCLS SHAB Characterization  
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Gap Change Visualization

Present Undulator

2nd Harmonic Undulator

Shim Size not changed in visualization
LCLS Undulator Phase Scheme

Cell: 3.656 m
Strongback: 3.400 m
112 Core Periods: 3.360 m

Phase Adjustment

K = 3.5000 (\lambda)

K = 2.2525 (\lambda/2)

Free Space Phase Slippage

LCLS SHAB Characterization Page 9
Undulator Roll-Away and K Adjustment Function

First; K=3.5000; Δx=-4.0 mm

Neutral; K=3.4881; Δx= 0.0 mm

Roll-Away; K=0.0000; Δx=+80.0 mm

Pole Center Line
Vacuum Chamber
Horizontal Slide

LCLS SHAB Characterization
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First SHAB Undulator Installed and Tested

- Gap of one undulator was increased and installed in slot U33 on 12/9/2009.
- Beam measurements done with the K-Mono

\[ E_e = 9.6 \text{ GeV} \]
\[ E_{x-ray} = 8.19 \text{ keV} \]
Required by K-Mono

\[ K = 2.24275 \]
\[ \Delta K/K = 1/161 \]
Installation and Test Schedule

• December 9, 2009
  SHAB U33 installed and tested @ 8.2 keV SHAB energy

• January – May 2010
  SHABs U29 – U32 modified, tuned, and installed

• May 2010 – August 2010
  SHABs commissioned as discussed in this talk

• Three more SHABs are ready to be installed

• Presently a maximum of 10 SHABs is considered

• Next steps are not yet decided
Diagnostics

- No absolute intensity measurement available (relying on eloss)
- Use various filters, attenuators, slits, YAG screens
- See talk by J. Welch (FROAI1) for discussion of x-ray diagnostics
Setup Steps

• Start with BBA (all undulator segments inserted)
• Set electron energy to target energy
  – 4.3 GeV (for 900 eV / 1800 eV) 2 keV 3\textsuperscript{rd} harmonic mirror cutoff
  – 6.2 GeV (for 4096 eV / 8192 eV) K-Mono
  – 14.2 GeV (for 9000 eV / 18000 eV) Zr K edge
• Setting a linear taper
• Remove SHABs
• Adjust electron energy to set 2\textsuperscript{nd} FEL harmonic to exact energy
• Insert 1 SHAB at a time and scan K and set to optimum
• Measure saturation point and set desired number of bunching undulators
Diagnostics for SHAB Energy = 8192 eV

- Use K Mono to remove fundamental and third harmonic.
- Use NFOV (Direct Imager) for observation.
- PROBLEM:
  K Mono very difficult to adjust

As example of use see K scan of U33, in earlier slide

End of Undulator

Transmits only 8192 eV

LCLS SHAB Characterization
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Diagnostics for SHAB Energy = 18000 eV

- Use Zr/Si foil to remove fundamental.
- Use deflection on HXR mirror pair to remove 3\textsuperscript{rd} harmonic.
- PROBLEM:
  
  HXR mirrors are too small for the beam.
  They are difficult to align to guarantee good 3\textsuperscript{rd} harmonic suppression.
  MD time too short to change machine energy from <2keV operation and tune.
Zr + Si Spectrum

Similar absorption at 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic

Thanks to Alan Fisher!

LCLS SHAB Characterization
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Bend energy 14.232 GeV

Background subtraction effectively removed non-beam background.

Above K edge intensity from $3^{rd}$ harmonic and leakage is quite low.
18 keV SHAB Energy

U1-33 all in (28+5 SHABs)

LCLS SHAB Characterization
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- Remove fundamental with wavelength dependent gas attenuator
- Remove third harmonic three consecutive mirrors (each with 2 keV cutoff)
- Use P3S2 YAG screen for detection. SXR spectrometer can be used if available and if signal strength is sufficient.
GainLength Gui

determine FEL saturation at ~11 undulator sections at SHAB energy of 1800 eV:

Remove first 17 undulators ➔

1800 eV SHAB Energy
Harmonic Bunching

Adjust number of regular undulators to optimize 2\textsuperscript{nd} harmonic microbunching in SHABs. Granularity is given by Segment Distance.

GENESIS simulation with $I_{pk}=1 \text{kA}$, $\epsilon_n=0.6 \text{\mu m}$, $\Delta p/p=10^{-4}$ at $E=4.5 \text{ GeV}$.
Debunching in SHABs due to Undulator $R_{56}$

- The FEL induced energy spread in the regular undulator is heating the electron beam
  - SHABs have an $R_{56}$
  - In an undulator $R_{56} = -\frac{K^2 L_u}{2\gamma_0^2} \approx -2N_u \lambda_r$

- When the $R_{56}$ of the SHABs spreads electrons by more than $\lambda_r/4$, the microbunching, built in the regular undulator, diffuses in the SHABs
  \[
  R_{56} \frac{\Delta \gamma}{\gamma} \approx \frac{\lambda_r}{4} \Rightarrow \gamma \approx \frac{1}{8\Delta \gamma / \gamma} \approx \frac{1}{8\rho}
  \]

- Take $\rho = 5 \times 10^{-4} \Rightarrow N_u \sim 250 \Rightarrow$ about 2 SHABs
- Of course, one can taper the SHABs to use more segments
- Higher energy FEL can have more SHABs, since $\rho$ is smaller

- The ratio of energy spread to bunching amplitude can be improved with a dispersive section acting on the pre-saturated bunch. (similar to HGHG scheme) L.H. Yu, Phys. Rev. A 44, 5178 (1991)
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GENESIS simulation with $l_{pk}=1$ kA, $\varepsilon_n=0.6$ µm, $\Delta p/p=10^{-4}$ at $E=4.5$ GeV.

2nd harmonic intensity

$0.5$ GW $\times$ $250$ fs $= 0.12$ mJ

Prediction for 1800 eV SHAB Energy
• First three data points are Und 26-28 (mostly 3\textsuperscript{rd} harmonic)
• Last five are SHABs (increase due to 2\textsuperscript{nd} harmonic bunching)
Kick electron beam transversely to destroy FEL and micro-bunching at selected point. Measure energy loss at dump BPM

1800 eV SHAB Energy

E\text{--Loss}=0.45\pm0.04 \text{ MeV (0.11 mJ)}, 20\text{--AUG--2010 21:58:24 (4.50 GeV)}

N\text{--photons}=7.74\times10^{11}
E\text{--photon}=0.90 \text{ keV}
\langle I_p \rangle = 900 \text{ A}

U16-33 inserted

E\text{--loss for U29-33}

P3S2 YAG signal during E\text{--loss scan}
More Exotic Eloss Scans

E-loss for U16-33

- Difference of two E-loss scan should be SHAB E-loss

0.54 - 0.46 = 0.08 mJ

LCLS SHAB Characterization
SHAB Taper improves 2\textsuperscript{nd} harmonic signal by a factor of 2

1800 eV SHAB Energy

\textbf{CONSTANT TAPER}

LCLS SHAB Characterization
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SHAB Taper improves 2\textsuperscript{nd} harmonic signal by a factor of 2

1800 eV SHAB Energy

DOUBLE INTENSITY

SHAB Signal on P3S2 YAG

EXTRA SHAB TAPER

LCLS SHAB Characterization
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Turning off the heater kills SHAB signal

Shows that SHABs act on microbunching; also demonstrates the importance of the Laser Heater

LCLS SHAB Characterization
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Summary

- Five SHABs generate ~0.1 mJ of 2nd harmonic power at 1.8 keV (barely detectable with E-loss method)
- Found increasing power over all five SHABs
- Reasonable agreement with simulations
- Signal is sensitive to Laser Heater setting
- Found that SHAB intensity at 18 keV (14.2 GeV) exceeds that of 3\textsuperscript{rd} harmonic at same photon energy (11.6 GeV) by at least factor 2
  - Measurement was suggested by J. Frisch
  - This factor should increase to 10+ if more SHABs are installed and beta-function is reduced.
- More SHABs are ready to be installed
- May wait until somebody can use the radiation before we install them

THANK YOU FOR YOUR ATTENTION!
End of Presentation